I – Problem Statement Title (EQ 122)

Seismic Design Guidelines for Bridge Column Piers on Pile Supported Foundations Allowed to Uplift

II – Research Problem Description

Question: How can Caltrans utilize existing construction technology to achieve bridge structures able to better resist the damaging effects of severe earthquakes, while sustaining less physical damage and permanent residual offsets that would impair post-event traffic flow and necessitate expensive inspections and repair?

Ductile design in combination with capacity design concepts permit modern bridge structures to develop without collapse the substantial inelastic deformations that can be required of fixed base structures by severe earthquakes. However, such bridges are susceptible to substantial damage and permanent lateral displacements that necessitate costly, time consuming, dangerous and disruptive inspections and long-term lane closures and repairs (and perhaps demolition). Recently, several approaches have been suggested to allow the bridge to undergo large inelastic deformations but to re-center following large earthquakes. These include (1) use of response modifications devices, such as seismic isolators, (2) partially prestressed reinforced or precast concrete columns, or (3) use of rocking foundations. Of these approaches, the use of rocking foundations introduces the fewest new technologies for the bridge designer and construction trades. Rocking of spread footings on soil is currently under study by Caltrans at UC Berkeley and UC Davis. While results to date are promising, the applicability of this approach is limited to cases where good soil conditions exist. Thus, it appears that such concepts should be extended to the more prevalent case where bridge piers are supported on piles. However, design approaches, simplified analysis procedures, structural details remain to be develop and verified via shaking table and other tests and numerical simulations.

III – Objective

STAP Roadmap Outcomes:

Research Outcome 8 - Improved performance of bridges and highway structures to earthquakes and other man-made and natural extreme events, and improved ability to quickly restore facilities to full functionality (Problem 1).

Bridge structures are expected to deform in the inelastic range when subjected to rare, but extreme man-made or natural events. Traditionally, this has been accomplished by permitting inelastic deformations to occur in a few select plastic hinge locations and capacity designing the remaining structural components to remain elastic. While this concept has been extensively validated through laboratory tests and actual earthquake experiences, considerable damage is produced in the structure, which can limit functionality and trigger severe impact to society in terms of traffic closures to allow costly repairs or even demolition and reconstruction. Thus, efforts have been made to introduce a number of different types of response modification devices, such as isolators and dampers. These require specialized design methods, and questions have been raised about their service life, methods of assessing their mechanical characteristics in situ, and the wisdom of straying from Caltrans long-term policy of constructing columns monolithically with the superstructure. Similarly, new concepts related to partially prestressed, reinforced or precast concrete columns appear highly promising, but questions exist about constructability, resistance to long-term corrosion and stress relaxation, and post-earthquake repair. Rocking foundations appear highly promising, but their applicability is limited to situations where the gravity load factor of safety of the spread footing is about 3 or higher, and the confidence that can be placed in the inelastic energy dissipation that can be provided by the supporting soil. Thus, because of the overall importance of this outcome to the functioning of the California transportation system following extreme events, it appears that research is need to demonstrate the feasibility of permitting rocking of pile supported foundations, and to develop and validate guidelines for design, analysis and detailing suitable for use by Caltrans and other bridge engineers.

Roadmap Outcome 5 - Improved Soil-Foundation-Structure-Interaction Analysis Tools, Techniques, and Methods (Problem 4)

This project also addresses the important issue confronting bridge engineers of improving the connection of the structure to the foundation. It has been noted in recent research at UC San Diego and elsewhere that the load distribution among piles fixed to a pile cap is more complex than it appears to be and may necessitate special detailing and increasing the size of the piles. Even so, undesirable damage at the pile-to-pile cap interface may be expected. By use of sleeved pile-to-pile cap connections as described below, the severity of these effects can be substantially reduced, and more reliable analytical models can be easily developed.

Roadmap Outcome 6 - Seismic Analysis and Design Tools, Techniques, and Methods (Problems 1 and 2)

This project proposes to use large-scale specimens tested at UC San Diego and UC Berkeley to provide important verification of design and analysis tools through component and system testing.

IV – Background

Following past earthquakes, and other unexpected occurrences (e.g., soil failures) bridge engineers have noted that older bridges may sustain far less damage than might be predicted by analysis. One reason for this is that the older connections of piles to pile caps, which support the bridge, are not able to develop the full capacity of the pile, and the piles inadvertently rock on top of the piles when the earthquake stops. This rocking bridge concept has been utilized in several major bridges, including the South Rangitikei Rail Bridge in New Zealand and the Lions Gate Bridge in Vancouver and several investigators are examining its applicability to steel truss piers and to spread footings.

Caltrans design practice has been to avoid rocking and develop sound details for connecting the piles to the pile cap (or providing adequate dimensions for a spread footing) and details for the pile cap and pile cap to bridge pier, to ensure the development of plastic hinges in the columns. In the case of fixed pile to pile cap connections, the large tensile forces that can develop in some piles (while others have large compression piles) tends to transfer much of the lateral load resisted by the piles to the piles in compression. Testing at UC San Diego has substantiated this observation and has prompted the need to reconsider the design of the reinforcement in piles. This might necessitate increasing the sizes of the piles or increase the amount of transverse and longitudinal reinforcement to avoid unanticipated damage in the pile-to-pile cap interface. This damage in the column, and piles, is difficult to assess and repair following an earthquake, and residual displacements may occur that impair post-event functionality. The consequence of this for bridges that are required to have full or limited operability following an earthquake is that columns are designed for higher force levels to reduce inelastic demands, and that the foundations become quite large and expensive (and the design forces in the superstructure also become large). Similar situations develop where bridges may be allowed to yield, but where the ground shaking may be unusually large. Thus, the concept of using rocking of pile caps on piles as a fuse limiting the forces that can be transmitted to the superstructure structure may provide a viable means of controlling the distribution of damage and the forces that can be developed in a bridge.

Research has indicated that rocking behavior in addition to modest amounts of energy dissipation can achieve peak displacement demands which are similar to those obtained with conventionally designed columns that form plastic hinges during severe excitations. However, rocking systems with center-oriented restoring force characteristics generally display little or no structural damage, including permanent residual displacements. Several means have been used for these types of systems to dissipate energy, generally involving hysteretic yielding elements that pass across the uplifting boundary. For example, buckling restrained braces, or metallic rods anchored in the pile and pile cap that are encased unbonded in a conduit, can conveniently and reliable provide such damping. In addition, success has been achieved by simply placing an electrometric or viscoelaistic material at the interface.

Research efforts should include:

1. Survey of available literature, including on-going research efforts.
2. Parametric investigations to compare damage associated with conventional fixed base column designs with positive pile-to-pile cap connections, with designs allowing rocking of the foundation. It is anticipated that the pile will be socketed into the pile cap, so that the pile on the uplifted side of the foundation still can transmit shear to the foundation without freezing up. However, since the pile will not have significant tensile force, it will be likely be more effective in resisting shear than a similar pile in a conventional design. The parameters for consideration would include the nature of the energy dissipation provided between the piles and the pile cap, the axial load

in the column, the aspect ratio of the column, type and arrangement of piles, the characteristics of the ground motion including the number of components of excitation. Initial emphasis will be place on simple bridge piers.

3. Analytical and experimental characterization of energy dissipation devices. The feasibility of simple passive devices to help facilitate post earthquake inspection of the various types of devices should be incorporated.
4. Analytical investigation into pile cap – pile pounding effects and development of details to mitigate the this effect.
5. Shaking table testing of single column bents supported on socketed piles under multiple components of motion.
6. Analytical investigations of complete bridge systems incorporating rocking foundations supported on piles.
7. Shaking table testing of a complete large-scale bridge system examining the interaction of bents having different properties, such as height, or foundation conditions.
8. Validation of analytical models based on large-scale test results.
9. Development and validation of guidelines for design, analysis and construction of bridge foundations supported on rocking foundations.

V- Statement of Urgency, Benefits, and Expected Return on Investment

It is a fact that there is a high probability of damaging earthquakes in many parts of California, particularly around the densely populated and technologically developed coastal areas. Similarly, demands for expanding the capacity of the transportation system are increasing as the population is increasing in many portions of California are increasing and with resulting increases in congestion and difficulty of transporting commercial goods vital to California's economy. As seen in recent hurricanes and earthquakes, disruption of critical infrastructure such as bridges has a disproportionate impact on the ability of a community or region to recover, and places considerable stress on limited available resources. The use of a methodology that would utilize existing construction technology and design approaches, while improving post-event operability, is considered to be cost effective and of high priority.

VI – Related Research

This work builds on recent and on-going research at UC Berkeley on rocking of bridge piers on spread footings, and at UC San Diego on fixed pile cap to pile connections and rocking shear walls. In addition, related research in the Americas, Japan, Taiwan, and Europe related to rocking foundations, related energy dissipation techniques, embedded passive sensors, and associated analysis and design methods would be reviewed and summarized.

References:

1. Mahin, S.A., Espinoza, A., "Rocking of Bridge Piers Subjected to Multi-Directional Earthquake Loading", 21st US Japan Bridge Engineering Conference, Tsukuba, Japan, October 2005.

2. Restrepo, J.I. Ha, I. and Priestley, M.J.N, "Seismic Behavior of Four CIDH Pile Supported Foundations", 21st US Japan Bridge Engineering Conference, Tsukuba, Japan, October 2005.

VII - Deployment Potential

The potential for deployment of this concept is significant once guidelines related to design; analysis and detailing are developed and verified by large scale testing. This work extends past work, and utilized design and construction techniques familiar to bridge designers and contractors. As such, it will likely avoid many of the impediments to implementation encountered when new and untried concepts are used. The ability of the approach to address design related problems associated with design of pile foundations on poor soil is also expected to accelerate deployment.